NON CONTACT METHOD AND APPARATUS FOR MEASUREMENT OF SHEET RESISTANCE OF P-N JUNCTIONS

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BACKGROUND OF THE INVENTION

The present invention relates to the measurement of the sheet resistance in the upper layer of p-n junction.

10   Advances in semiconductor technology increase requirements to monitor epi and ion implant sheet resistance, Rs, in the range 50 - 5000 ohms/square.

Currently 4-point probe technique is widely used for sheet resistance measurement. In the case of ultra shallow p-n junctions this technique has disadvantages: mechanical probes can poke through the implant layer; and probe pressures necessary for

15   making ohmic contact with an implant layer can create P-N junction leakage between the implant layer and the underlying opposite conductivity substrate.

For these reasons, the 4-point probe techniques are inadequate for the requirements of ultra shallow P-N junction monitoring needs.

Non-contact surface photovoltage (SPV) technique can be used for measurement

20   of the sheet resistance. SPV is the change of the near surface bad bending or surface barrier under intensity modulated illumination. As usually SPV is picked up by transparent and conducting electrode brought near wafer surface illuminated area and used for measurement of the minority carrier diffusion length, near surface lifetime and doping level. In the case of strong inversion (for example if top surface of oxidized wafer

25   p-type conductivity is charged with positive ions) SPV can propagate outside of illuminating area due to lateral diffusion and the drift of the electrons and holes [V.N.

Ovsyuk. Lateral diffusion of the minority carriers in thin semiconductor films, Sov. Phys. Semicond., v.16, p. 2146 (1982)].

The theory and experimental evidence of SPV propagation outside the illumination area in the silicon wafers with strong inversion surface condition was published in V. Faifer et.al. Measurement of the diffusion length with improved spatial resolution, *Proceedings of 24th ESSDERC'94*, Edinburgh, p.601 (1994). The propagating of SPV outside the illumination area strongly depends on the sheet resistance of inversion layer or upper layer of p-n junction. The SPV equation described in this paper can be used also for calculation of SPV spatial distribution as function of coordinate x, y, light modulating frequency, sheet resistance and conductance in the case of silicon wafers in strong inversion or ultra shallow p-n junctions.

The non contact SPV technique for measurement of sheet resistance in ultra shallow p-n junctions was proposed in US Patent to Roger L. Verkuil, #5,442,297 in 1995. This technique is based on the measurement of surface photovoltage (SPV) signals outside a local illumination area. To detect the attenuation and phase monitoring the apparatus include two conducting rings placed in the vicinity of the wafer surface outside the illumination area. Using the measurement of two AC SPV signals outside the illumination region and junction capacitance data the sheet resistance can be calculated.

This technique has follows disadvantages: since only attenuated SPV signals are measured outside the illumination area this approach can not provide good enough spatial resolution and high sensitivity for measurements of sheet resistance Rs<400 Ohms/square in ultra shallow P-N junction with high dose of implant. The measurement is based on small signal linear SPV theory. According to this theory SPV signal should be linear

versus light flux not only outside illumination area but also inside this area. The _____ technique presented in US patent #5,442,297 uses measurement only outside illumination area. The calculation of sheet resistance is based on simplified model valid only for infinitely thin metal rings electrodes. As a result this model will give additional

5   systematic error since capacitance of these thin electrodes should depends non linear on its distance from the wafer surface and linearity condition does not checked within illumination area. This probe configuration does not allow produce accurate measurement close to the edge of the wafer.

The advantages of present invention are to provide a method and apparatus for

10 accurate measurements of sheet resistance of less than 400 Ohms/square with improved spatial resolution and sensitivity.

SUMMARY OF THE INVENTION

An object of this invention is to provide a non-contact sheet resistance apparatus

15 for measurement for low medium and high dose implant layers. The present embodiment of the invention apparatus includes means for illumination area of semiconductor structure, a transparent and conducting electrode installed near the surface of the semiconductor wafer directing light onto its surface and detecting SPV signal from said area. The present invention also includes a second electrode detecting SPV signals

20 outside the illumination area. The second electrode can be a metal ring coaxial with transparent and conducting disk of the first electrode. The second electrode can be a metal arc, which installed to be under the wafer, even if the light spot and transparent

electrode are located at the edge of the wafer. Using this configuration of the second electrode, the edge effect can be significantly decreased.

Another object of the invention is to provide a method for measurement of sheet resistance. To obtain accurate measurements, the intensity of the light is adjusted to obtain the linear dependence of SPV signal from transparent electrode versus light flux.

The first method uses measurement of the SPV signal only from the first electrode. This method requires the calibration using the wafer with known sheet resistance. The method is based on comparison of SPV signal for wafer with unknown sheet resistance and calibration wafer with Rs measured using 4-point probe. This calibration wafer should have thick enough upper layer of p-n junction to get accurate 4 point probe measurement. The procedure of measurement includes the following steps:

a) Illumination the area of the semiconductor structure with known sheet resistance through transparent electrode with intensity modulated light;

b) Measurement of the SPV signal from transparent electrode;

c) Adjustment of the light flux to get linear dependence of the SPV signal versus light flux;

d) Measurement of SPV signals $Vs0$;

e) Measurement of SPV signal $Vs1$ at the same conditions for wafer with unknown Rs;

f) Determination of the sheet resistance using measured $RATIO = Vs1/Vs0$, and the calculated curve or table $RATIO\ (Rs)$.

The second method uses measurement of the SPV signals from the first electrode and second electrodes and provides the measurement of the sheet resistance without calibration sample. The procedure of measurement includes the following steps:

a) Illumination the area of the semiconductor structure through transparent first electrode with intensity modulated light at maximum frequency, *Fmax*, corresponding bandwidth of SPV preamplifier and lock-n amplifier;

b) Measurement of the SPV signal, *Vs1*, from transparent electrode;

c) Adjustment of the light flux to get linear dependence of the SPV signal, *Vs1*, versus light flux;

d) Measurement of SPV signals, *Vs1* and *Vs2* from the transparent and not transparent electrodes;

e) If Vs1/Vs2>5 decreasing light modulating frequency to get the ratio of SPV signals *RATIO=Vs1/Vs2<5* and measurement of Vs1 and Vs2 at this frequency;

g) Determination of the sheet resistance using measured *RATIO=Vs1/Vs2*, and the calculated curve or table *RATIO (Rs)*.

The third method uses measurement of the SPV signals and phase shifts from the first and second electrodes and provides the measurement of the sheet resistance and conductance of p-n junction. The procedure of measurement includes the following steps:

a) Illumination the area of the semiconductor structure through transparent first electrode with intensity modulated light at maximum frequency, *Fmax*, corresponding bandwidth of the SPV preamplifier and lock-in amplifier;

b) Measurement of the SPV signal, *Vs1*, from transparent electrode;

c) Adjustment of the light flux to get linear dependence of the SPV signal, *Vs1*, versus light flux;

d) Measurement of SPV signals and its phase shifts, *Vs1, Θ1* and *Vs2, Θ2* from first transparent and second non transparent electrodes;

e) If Vs1/Vs2>5 decreasing the light modulating frequency to get the ratio of SPV signals *RATIO=Vs1/Vs2<5* and measurement of *Vs1, Θ1* and *Vs2, Θ2* at this frequency;

f) Determination of the sheet resistance Rs and junction conductance Gs using measured SPV signals and its phase shifts, *Vs1, Θ1* and *Vs2, Θ2*.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig.1 is a pictorial view of the present embodiment of the invention.

Fig. 2 is a pictorial view of a first SPV probe configuration.

Fig. 3 is a pictorial view of a second SPV probe configuration.

Fig. 4 is a pictorial view of the configuration of SPV electrodes with respect to the wafer.

Fig. 5 is a pictorial view of the calculated dependence of the ratio of SPV signal from first electrode versus sheet resistance normalized on SPV signal for p-n junction with sheet resistance Rs=400 Ohms/square.

Fig. 6 is a pictorial view of the calculated dependence of the ratio of SPV signals from first and second electrodes versus sheet resistance.

DETAILED DESCRIPTION OF THE APPARATUS AND METHOD

In Fig.1, a contactless sheet resistance measurement apparatus 1 is shown. Wafer 2 is placed on a wafer chuck 3. The wafer chuck is placed on the rotary stage 4. The rotary stage 4 is installed on the linear stage 5. The apparatus comprises an SPV probe 6, which is placed close to the wafer surface and optically coupled through fiber bundle 8 with the LED 7, connected to the LED driver 9. Two electrical outputs of the SPV probe 6 are connected to the lock-n amplifiers 10 and 11. Lock–in amplifiers 10 and 11, step motors of stages 4 and 5 are electrically connected to interface and computer 12.

SPV probe 6 represented at Fig.2 includes dielectric ring 13, a glass disk with transparent and conducting ITO coating 14, two metal electrodes like the rings 15 and 16. Conducting layer of glass disk 14 is connected to preamplifier 17, metal electrode 15 is grounded and metal electrode 16 is connected to the preamplifier 18. The output of preamplifier 17 is connected to the lock-in amplifier 10 and output of preamplifier 18 is connected to the lock-in amplifier 11.

SPV probe 6 represented at Fig.3 includes dielectric ring 13, a glass disk with transparent and conducting ITO coating 14, two metal electrodes like the part of the ring 15 and 16. Conducting layer of glass disk 14 is connected to preamplifier 17, metal electrode 15 is grounded and metal electrode 16 is connected to the preamplifier 18. The output of preamplifier 17 is connected to the lock-in amplifier 10 and output of preamplifier 18 is connected to the lock-in amplifier 11. As shown at Fig.4 the SPV probe is installed to provide the electrodes 15 and 17 inside the wafer, when transparent electrode 14 is close to the edge of the wafer.

The method of measurement is based on the solution of the equation for SPV value as function of coordinate x, y, derived in publication the *Proceedings of 24th ESSDERC'94*, Edinburgh, p.601 (1994). After some modification the equation can be written as:

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$$\frac{\partial^2 v_{SPV}}{\partial x^2} + \frac{\partial^2 v_{SPV}}{\partial y^2} = Rs \cdot Cs \cdot \frac{\partial v_{SPV}}{\partial t} + Rs \cdot G \cdot v_{SPV} - q \cdot \varphi \cdot (1 - R) \cdot Rs \tag{1}$$

where: $v_{SPV}(x, y, t)$ is SPV value as function of coordinates x, y;

$\varphi(x, y, t)$ is the intensity of light flux;

Rs is the sheet resistance of the upper layer of p-n structure;

Cs is the capacitance of p-n junction per unit area;

10   G is the conductivity of p-n junction per unit area;

R is reflectivity of semiconductor.

The conductivity of p-n junction can be determined as:

$$G = \frac{I_0 \cdot q}{k \cdot T} \tag{2}$$

where q is charge of the electron;

15   k is Boltzman constant;

T is the temperature;

Io is the prefactor in formula of current, I, versus voltage, V, of p-n junction:

$$I = I_0 \cdot [\exp(q \cdot V / kT) - 1] \tag{3}$$

The capacitance of the p-n junction can be calculated using formula:

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$$Cs = \sqrt{\frac{\varepsilon_{SI}\varepsilon_0 q^2 N}{2kT}} \bigg/ \sqrt{2\ln\left(\frac{N}{ni}\right) + \ln\left(\ln\left(\frac{N}{ni}\right)\right)} \qquad (4)$$

where:

ε_0 is the permittivity of vacuum;

ε_{SI} is the permittivity of silicon;

q is the magnitude of electronic charge;

kT is the thermal energy;

ni is the intrinsic concentration of charge carriers in semiconductor; and

N is concentration of the majority carriers in semiconductor substrate.

The SPV signal can be calculated using the formula:

$$V_{SPV}(t) = Const \iint_S v_{SPV}(x, y, t)dxdy \qquad (5)$$

where S is the area of electrode, *Const* is the value, which depends on the air gap between electrode and the semiconductor surface, the gain of amplification of the preamplifier and others parameters.

In the case of sinusoid modulated light SPV signal can be represented as:

$$V_{SPV}(t) = V_S \cdot \exp(j\omega \cdot t) = |Vs|\exp(j\theta)\exp(j\omega \cdot t) \qquad (6)$$

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where $/Vs/$, ϑ are the magnitude and phase shift of SPV signal, Vs, $\omega = 2\pi F$, F is light modulating frequency.

Using the equation (1), formula (5) we can get the formulas for SPV signals from electrodes installed inside, Vs1, and outside, Vs2, the illumination area:

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$$V_{S1} = \frac{q\Phi R_S}{k^2}\left[1 - \frac{2}{kR_0}\frac{I_1(kR_0)K_1(kR_0)}{I_0(kR_0)K_1(kR_0) + I_1(kR_0)K_0(kR_0)}\right] \tag{7}$$

$$V_{S2} = 2q\frac{\Phi R_S}{k^3 R_0^2}\frac{I_1(kR_0)[R_1 K_1(kR_1) - R_2 K_1(kR_2)]}{I_0(kR_0)K_1(kR_0) + I_1(kR_0)K_0(kR_0)} \tag{8}$$

where

$$k = \sqrt{RsG + j\omega RsCs} \tag{9}$$

10    $I_0(z)$, $I_1(z)$, are the modified Bessel function of the first kind;

$K_0(z)$, $K_1(z)$ are the modified Bessel function of the second kind;

R_0 is the radius of the first transparent electrode;

R_1, R_2 are the inner and outer radiuses of the second non transparent electrode;

Φ is the effective light flux propagating inside semiconductor.

15   If light modulating frequency is high enough, $\omega >> G/Cs$, SPV signal does not depend on leakage of p-n junction and sheet resistance can be calculated using measured values of the magnitudes of SPV signals from first transparent electrode, Vs1, and second non transparent electrode and equation:

20 $$\frac{Vs1}{Vs2} = \left|\frac{V_{S1}}{V_{S2}}\right| = \left|\frac{1}{2}kR_0^2\frac{K_1(kR_0)I_0(kR_0) + K_0(kR_0)I_1(kR_0) - (1/2kR_0)K_1(kR_0)I_1(kR_0)}{I_1(kR_0)[R_1 \cdot K_1(kR_1) - R_2 K_1(kR_2)]}\right| \tag{10}$$

where Cs is calculated using formula (5);

$$k = \sqrt{j2\pi F R_s C_s}$$

For leaky p-n junctions and low frequency, F, sheet resistance and conductance can be calculated using the measured magnitudes and phase shifts of SPV signals $Vs1,\theta1$ and $Vs2,\theta2$, and a set of equations:

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$$\frac{Vs1}{Vs2} = \left| \frac{V_{S1}}{V_{S2}} \right| = \left| \frac{1}{2}kR_0^2 \frac{K_1(kR_0)I_0(kR_0) + K_0(kR_0)I_1(kR_0) - (1/2kR_0)K_1(kR_0)I_1(kR_0)}{I_1(kR_0)[R_1 \cdot K_1(kR_1) - R_2 K_1(kR_2)]} \right| \quad (11)$$

$$\theta_1 - \theta_2 = Arg\left[\frac{1}{2}kR_0^2 \frac{K_1(kR_0)I_0(kR_0) + K_0(kR_0)I_1(kR_0) - (1/2kR_0)K_1(kR_0)I_1(kR_0)}{I_1(kR_0)[R_1 \cdot K_1(kR_1) - R_2 K_1(kR_2)]} \right] \quad (12)$$

The results of calculation using formula (7) SPV signal from transparent electrode versus sheet resistance for light modulating frequency f=100 kHz and the diameter of transparent electrode 5 mm is represented at Fig. 5. This curve is normalized on SPV

10 signal for p-n junction with sheet resistance Rs=400 Ohms/square. The substrate doping concentration is 10^{15} cm^{-3}.

Fig. 6 shows the calculated using formula (10) dependence of the ratio of SPV signals, Vs1/Vs2, from first and second electrodes versus sheet resistance for light modulating frequency f=100 kHz, diameter of the transparent electrode is 5 mm, the

15 inner and outer diameters of the metal ring electrode are 16 and 18mm. The substrate doping concentration is 10^{15} cm^{-3}.

The first method uses measurement of the SPV signal from the first electrode. This method requires the calibration using the wafer with known sheet resistance. The method is based on comparison of SPV signal for wafers with unknown sheet resistance

20 and calibration wafer with Rs measured using 4-point probe. This calibration wafer

should have thick enough upper layer of p-n junction to get accurate 4 point probe measurement

The procedure of measurement includes the following steps:

a) Illumination the area of the semiconductor structure with known sheet resistance through transparent disk **14** with intensity modulated light at frequency, f, from LED **17**;

b) Measurement of the SPV signals **Vs0** from transparent electrode **14**;

c) Adjustment of the light flux to get linear dependence of the SPV signal $Vs0$ versus light flux;

d) Measurement of SPV signal $Vs0$; Measurement of SPV signal $Vs1$ at the same conditions for wafer with unknown Rs;

e) Determination of the sheet resistance using measured $RATIO=Vs1/Vs0$, and equation(7).

The second method uses measurement of the SPV signal from the first and second electrodes. The procedure of measurement includes the following steps:

a) Illumination the area of the semiconductor structure through transparent disk **14** from LED **17** with intensity modulated light at frequency, $Fmax$, corresponding to bandwidth of SPV preamplifier and lock-n amplifier;

b) Measurement of the SPV signal, $Vs1$, from transparent electrode;

c) Adjustment of the light flux to get linear dependence of the SPV signal, $Vs1$, versus light flux;

d) Measurement of SPV signals, $Vs1$ and Vs2 from electrodes **14** and **16** respectively using preamplifiers **17** and **18**;

e) If Vs1/Vs2>5 decreasing of light modulating frequency to get the ratio of SPV signals $RATIO=Vs1/Vs2<5$ and measurement of SPV signals at this modulating frequency;

f) Determination of the sheet resistance using measured $RATIO=Vs1/Vs2$, and equation (10).

For leaky p-n junctions condition $\omega >> Gs/Cs$ can not be valid even for high frequency F>10 kHz. In this case the additional measurement of the SPV phase shift should be provided and Rs, Gs can be calculated using set of equations (11), (12), where $Vs1$, $Vs2$ and $\Theta1, \Theta2$ are the measured magnitudes and phase shifts of SPV signals from first transparent and second non transparent electrodes.

The third method uses measurement of the SPV signals and phase shifts from the first and second electrodes. The procedure of measurement includes the following steps:

a) Illumination the area of the semiconductor structure through transparent disk **14** from LED **17** with intensity modulated light at frequency, $Fmax$, corresponding the bandwidth of SPV preamplifier and lock-in amplifier;

b) Measurement of the SPV signal, $Vs1$, from transparent electrode;

c) Adjustment of the light flux to get linear dependence of the SPV signal, $Vs1$, versus light flux;

d) Measurement of SPV signals and its phase shifts, $Vs1, \Theta1$ and $Vs2, \Theta2$ from electrodes **14** and **16** respectively using preamplifiers **17** and **18**;

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e) If Vs1/Vs2>5 decreasing the light modulating frequency to get the ratio of SPV signals *RATIO=Vs1/Vs2<5* and measurement Vs1 and Vs2 at this modulating frequency;

f) Determination of the sheet resistance Rs and junction conductance Gs using measured SPV signals and its phase shifts, *Vs1,Θ1* and *Vs2,Θ2* and set of equation (6) and (7).